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K-BAND ECHO LINE

REPORT
974

RADIATION LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE · MASSACHUSETTS

NDRC
Div. 14
OEMsr-262

Radiation Laboratory

Report 974 **March 26, 1946**

K-BAND ECHO LINE

Abstract

An echo line is a long waveguide in which the radar pulse re-echoes, producing a series of pulses on the indicator for test purposes. The fabrication and testing of an 18" helix of oversize K-band waveguide, 150' long, is discussed. Tests showed the attenuation to be .029 db/foot, which suggests the use of such oversize waveguide for radar transmission lines.

J. M. Wolf

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Title page
14 numbered pages

K-BAND ECHO LINE

It has been suggested from many sources that an easy test of radar performance would consist of introducing a sample of the radar pulse into a very long transmission line of known attenuation and observing the amplitude of the pulse, delayed and attenuated by this line, with the radar receiver.

This sort of a testing device has been dubbed an "echo line". Echo lines have not been employed outside of the laboratory, but have important potentialities for future production application.

In the current thinking, an echo line is coupled to a radar by means of a directional coupler and an RF switch. The switch permits the device to be turned off when not in use. The echo line has a round-trip length greater than that of the radar pulse, and is provided with a short at the far end. On the input end a mis-match is provided to reflect the pulse for another circuit of the echo line each time the pulse returns.

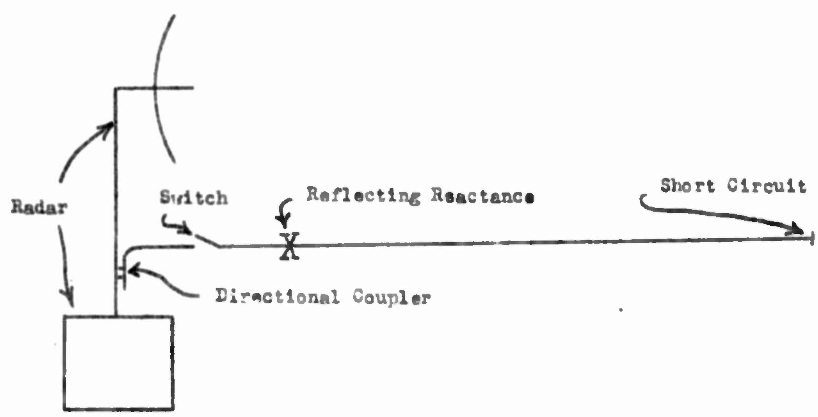


Figure 1. A Diagram of an RF Echo Line Attached to a Radar.

In use, a fraction of the radar pulse enters the echo line via the directional coupler when the switch permits. A large portion of this energy is reflected by the reactance, however a portion enters the echo line proper. This pulse travels to the short circuit and is reflected back toward the input end. At the reactance a major portion of the pulse is reflected back toward the short again, but a fraction of the energy enters the radar via the directional coupler and appears as a pulse.

The pulse continues to reflect back and forth in the line, on each trip producing a pulse in the radar. Each pulse of this series is weaker than the preceding because of the attenuation of the echo line. Finally the pulses become so weak that the radar receiver cannot detect them. By counting the number of pulses visible and estimating the strength of the last pulse one may know whether the radar performance is satisfactory. It has been suggested that an attenuator be placed between the switch and the reflecting reactance to allow one to adjust the amplitude of the nth pulse. One would then read the performance from the attenuator.

Notes on the choice of the reflection coefficient of the iris are presented in Appendix A.

It is plain that the major problem lies in the construction of the echo line itself. Assuming the group velocity of the pulse to be c, an echo line must have a length of a considerably greater than 164 yards per microsecond radar pulse length. The line must also be of small bulk and of low attenuation. These are difficult conditions to meet, therefore the device seems practical only when the pulse length is very short.

In order to reduce the bulk of an echo line substances of high dielectric constant have been considered. The attenuation of these materials, having dielectric constants of from 200 to several thousand is unfortunately too high at present to permit their use at K-band, and in addition their dielectric properties are prone to be very temperature sensitive. Such a dielectric filled line was built, but it was not tested.

The bulk of an echo line will be too great unless coax or small waveguide can be used and unless the pulse length is very short. The value of an echo line seems likely to be greatest at K-band, where adequate echo boxes are excessively difficult to make and where small waveguide and short pulses are used.

Several echo lines have been constructed and operated, by Jane and William Fairbank and by Virgil Counter. These were made of X-band waveguide used at K-band and X-band respectively. They served to demonstrate that an echo line operates as expected. These were not compact, being composed of long straight sections of line and few bends, and they were not of ideal dimensions.

Dr. Alfredo Baños designed an echo line theoretically suitable for K-band use. This line consists of a rectangular waveguide operated in the TE_{01} mode. The waveguide is of such dimensions that the TE_{02} mode but not the TE_{03} mode may be propagated. By avoiding H-plane bends he hoped that other modes would not be excited. The internal dimensions and properties of this line as calculated are:

[724 x 883, (E vector parallels longer dimension)

λ_c = 4.48 cm, TE_{01} mode

attenuation: 16 db/microsecond

temperature sensitivity of attenuation:
-1%/10° F, normalized at 70° F]

The fabrication of such a line for Project Cindy was desired but for some time no feasible means of construction was conceived. A line 150 feet in length was needed, which implies that the wall thickness could not be great if the weight was to be kept small. Thin walled tubing of the desired form was drawn but it was found that it could not be bent successfully. It was hoped that a concern could be found which would attempt to extrude a coiled tubing, however this could not be done. Other means considered were "electro-forming" on wax cores, chemical deposition followed by electroplating inside of plastic tubing, and the assembly of stamped sections. Various objections made each of these processes seem impractical.

A coiled line was finally prepared by hydraulically expanding round tubing into a mold. The forming of the line is treated by Mr. Flavin in Appendix B.

Two sections of coiled echo line were given attenuation tests as described in Appendix C, and the attenuation was found to be about .029 db per foot at K-band. This attenuation should permit successful use of these sections as an echo line. Successive pips should differ by 8.7 db for a 150 foot length of line, not including loss at the iris. See Appendix A.

It seems that transmission line of this low attenuation should find general application in radar design as well as this specialized use. It should be noted that the attenuation is as low as that of 7/8" coaxial line at S-band.

James H. Wolf
December 31, 1945

Appendix A

Choice of the Reflection Coefficient of the Iris

Given as an object the presentation of a maximum number of echo pips upon the screen from an echo line, the following derivation leads to a choice of the proper reflection coefficient for the reactive iris placed in the echo line. At the iris there is a voltage reflection factor of α, therefore the reflected power is proportional to α^2.

The power transmitted must be proportional to $(1 - \alpha^2)$ by convervation of energy.

After the energy has entered the line, on each reflection from the iris there is a loss in level at each reflection from the iris because of energy which leaves the line.

Taking these into account we may write an expression for the power of each pip reaching the receiver from the echo line as:

1) $P_r = P_t\, C^2\, \alpha^4\, (1 - \alpha^2)^{N-2}\, A^{2(N-1)}$

when:

P_r = power of the Nth pip reaching receiver

N = serial number of the pip, "main bang" = No. 1 pip

P_t = pulse power of the "main bang"

C = coupling of the directional coupler, expressed as a power ratio of less than one

α = absolute magnitude of the voltage reflection coefficient of the iris.

A = one-way attenuation of the echo line, as a power ratio of less than one.

We may maximize the strength of the Nth pip, given the values of P_t, C, and A as constants:

2) $$0 = \left.\frac{\partial P_r}{\partial \alpha}\right]_{N,\, P_t,\, C,\, A} = P_t\, C^2\, A^{2(N-1)} \left[-2\,(N-2)\,\alpha^5\,(1-\alpha^2)^{N-3} + 4\,\alpha^3\,(1-\alpha^2)^{N-2}\right]$$

dividing by $2P_t C^2 A^{2(N-1)}\, \alpha^3\, (1-\alpha^2)^{N-3}$,

3) $0 = -(N-2)\,\alpha^2 + 2\,(1-\alpha^2)$

4) $\alpha = \sqrt{\frac{2}{N}}$

The most direct approach to the remainder of the problem is to calculate the strength of each of the pips in the region in which the last pip may be expected to fall, and for each calculation use that value of α given by equation 4. That value of α should be employed which is associated with the last pip found to have a power greater than the minimum discernible signal of the radar.

The reactive device which is the embodiment of the reflection coefficient a must be fixed in value, not an adjustment. It must not excite higher modes in the guide, which probably implies that it should be a quite symmetrical device. It should not be placed in the small size transmission line; before transformation into the echo line. The design of this reactance is not expected to be difficult.

Appendix B

Hydraulic Formation of "Cindy Echo Line"
(Radiation Laboratory Project 1004)

W. K. Flavin

This report has been framed with the view.

1. To describe briefly and generally the steps and treatments used to form successfully the first echo line material.

2. To discuss some of the features of the drawing operation

3. To advise of possible future improvements in the process which the lack of time and materials did not allow us to investigate.

Method of Hydraulically Drawing "Echo Lines"

Materials Used

1. A cast iron mould of two pieces (as shown in Figure 2).

2. Annealled copper tubing in a coil approximately 4' in diameter of 75' length, .750' O.D. (circular cross-section) and .027" ±.003 wall thickness.

3 A hand-operated, piston-type pump capable of delivering 10,000 lbs/in 2 pressure with gauges for pressure determination and volume measuring means, reading volumes pumped to 10 cc increments.

4. Some of the more important miscellaneous operating equipment and fittings are:

   a. End-plug of brass .690" O.D. (round) and 1¼" long.

   b. Inlet fitting and two flare supports. See Figure 3.

   c. A metal-flow lubricant of beeswax loaded, approximately to 40% by volume, with graphite and diluted with 40% of carbon tetrachloride. This mixture is a thin paste which can be painted in place with a brush and which dries to a heavy bodied film for high-pressure lubrication.

   d. A one ton chain hoist.

   e. Approximately 3' lengths of 4" or 5" deep steel I-beam stock.

   f. Jacking equipment to open mould when coil has been formed in it.

   g. Acetylene torch equipment.

Procedure

Coat the bottom surface (that surface at the 16" diameter side of moulding recess) with the graphite and wax lubricant, being careful not to

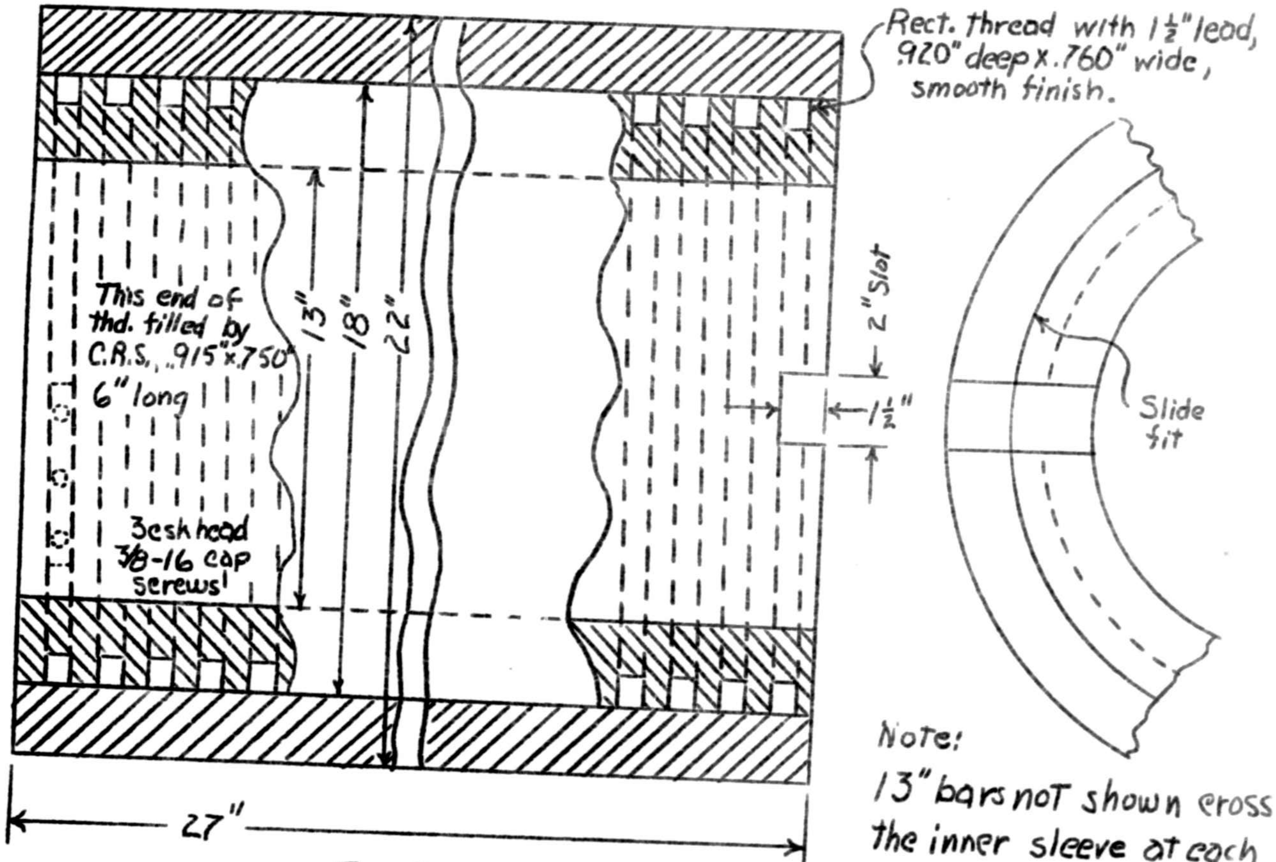
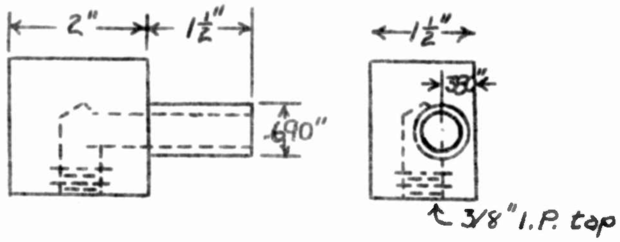


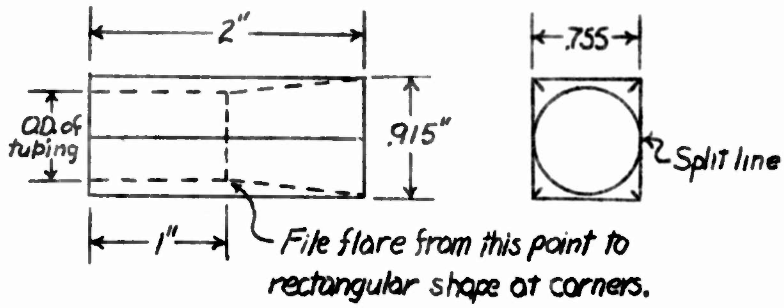
Fig. 2: Cast Iron Mould

Note:
13" bars not shown cross the inner sleeve at each end, for handling.

Figure 3



Brass Inlet Fitting



Brass Flare Support, 2 req'd.

get lubricant in appreciable amounts on the two side-wall surfaces of the moulding recess. Mount the threaded sleeve of the mould directly over the outer sleeve, by suspending it from a chain fall both with their axes vertical and with outer sleeve standing on its end. Silver-solder (for 1" to 1-1/4" depth of seal) a plug .690" in diameter and 1½" long in one end of the copper tubing. Start this plugged end of coil in the mould thread beginning the coiling with the plug against the steel strap stops of the mould. Place a flare support around the plugged end. Wind the copper tube into the thread with an effort to push the coil into the mould and thus get an 18" outside diameter. By dropping the threaded sleeve of mould into the outer sleeve, as each turn is wound into the thread, the coil may be controlled. When the coiling has reached the 2" wide slot at the top of the mould, cut off the copper coil flush with the side of the slot. Silver solder the inlet fitting to the copper tube, bending tube back out of mould during soldering. Put a flare support over the inlet fitting and bend the tubing again into mould thread, placing the 2" block in the recess at the mould top milled to receive it.

When the inlet block has been properly seated in the 2" slot the mould can be completely closed with coil in position. Fill coil with water and connect the inlet block with 3/8" pipe to the pump. Pump water into the coil until 400 lbs/in^2 pressure is indicated on the pressure gauge. Absorption of slight quantities of trapped air will let the pressure drop in 1/4 to ½ hour. Renew pressure at the 400 lbs/in^2 level until it will remain without loss for ½ hour. Examine mould for leaks of fittings and coil through this period.

When filling the coil with water measure the volume of water as it is placed in the coil. Use this inserted volume as a base for calculation and pump a computed 35% of this volume into the filled coil. The copper should begin to draw at around 1000 lbs/in^2. As water is pumped, the pressure will rise to 2000 to 2200 when the 35% is fully pumped into coil. Disconnect the pumps from coil and raise the threaded-mould sleeve bearing the partially-drawn coil with the chain hoist.

This partially drawn coil is to be removed from mould and annealed. To remove the coil from mould, first withdraw a small amount of water from the coil and head the inlet block with a torch to unsolder it from the coil. When the block has been removed, force lubricating oil between the coil and the mould. Screw the coil upward and off the threaded sleeve. Remove the remaining water from coil; unsolder bottom plug (.690" diameter) from coil and anneal coil in a non-oxidizing atmosphere.

Re-solder the plug back to the annealed coil and screw the coil back over the threaded sleeve. Give the outside surface of the coil, the surface in view when the coil is in position on the sleeve, a thin coating of the graphite lubricant. Re-solder the inlet plug on the entrance to the coil. Fill the coil with water and test fittings and soldering with 400 lbs/in^2 as in the first run.

When pressure stability indicates all air has been absorbed, pump water into the coil. It will again start to draw at about 1000 lbs/in^2. At 2000 lbs/in^2 pressure will rise more rapidly and pumping should be carried on to a gauge reading of about 4000 lbs/in^2. In the first try the soldered fittings ruptured at 4000 lbs/in^2 but sufficient drawing had been obtained.

To remove the coil from threaded mould-sleeve drill a line of 1/8" holes in the coil adjacent to inlet block. With a cold-chisel, cut the inlet block free of the coil and after forcing lubricating oil between coil and threaded sleeve, unscrew the coil from the mould.

Trim both ends of the coil with a hack saw, wash the graphite lubricant from coil with kerosene and wipe dry.

Figure 4 gives the pressure required to draw the echo line. In the upper portion of the figure data on two first drawings are presented. The coil which drew at lower pressure had been annealed, the other had not. Both coils, it may be noted, ruptured after 2100 cc had been injected. The calculated volume of the tubing before drawing was 5610 cc, therefore rupture occurred at 137% base volume. One of the coils, the one not annealed, was repaired after rupture and drawing was continued. The coil promptly ruptured again as indicated.

In the lower portion of the figure data are presented on the second drawing.

<u>Discussion of Process Limitations and Technique Details</u>

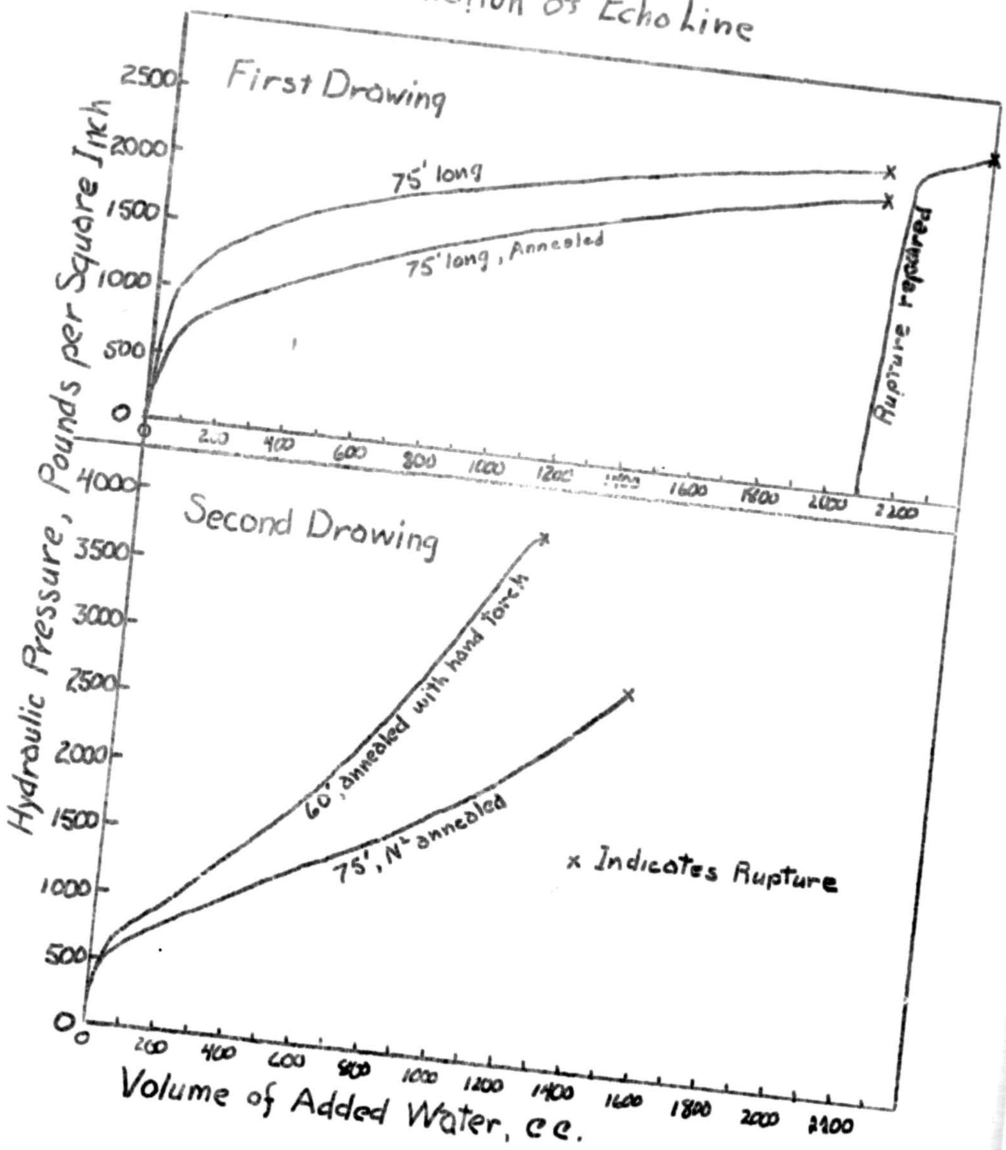
The graphite lubrication advice given under "procedure" has as a purpose remedying localized drawing affects. The side walls of the thread, being separated by the smallest dimension, start to support the drawn metal first. The coils flatten out on these side walls first. The inside and outside (16" and 18" diameter) faces of the coil, having curvature, seem to resist being drawn so the flat sides of tube draw almost exclusively. Having graphite lubrication on the inside and outside (16" and 18" diameter) faces only, will cause the metal to cling to the side walls, as pressure seats it flatly there and allows the curved inner and outer faces to contribute their share of the drawing.

The 35% volume increment based on the water-filled volume of the coil was established as a "flow limit" of the tubing. Several experiments indicates that thoroughly annealed tubing could not be given a volumetric stretch of over 40% of starting internal water-volume base. At 40% the metal is worked-hardened to a rupture point. Annealing renews this 40% drawing range or nearly so. In our attempts no drawing of copper beyond 40% starting water volume was accomplished. Hence, the recommended 35% volume limit of the first drawing of the coil.

When the second drawing of coil (the 4000 lbs/in ^{2} draw) is made the mould is quite firmly frozen up. The coil is so firmly pressed against the sleeve that a combination of a 5" I-beam and a hydraulic jack were required to draw the inner threaded sleeve and coil out of the outer-mould sleeve. The smoothness of the outer sleeve and lubricants used do not give rise to tearing of the copper coil by the use of such powerful equipment. When the coil and inner threaded sleeve of the mould are removed, the release of pressure resulting frees the copper coil immediately. The forcing of lubricating oil between coil and threaded mould sleeve make it possible to screw the coil from the threaded recess it is formed in without distorting it from the drawn shape.

Figure 4

Formation of Echo Line



Suggested Improvements of Method

There are two major improvements which seem obvious to the writer and which time have left untried.

1. The tubing size used resulted in a final rectangular-sectioned coil of wall thickness of approximately .020". This wall thickness, when drawn with 4000 to 5000 lbs/in^2, results in corners which are rounded with an inside radius of 1/16". This 1/16" radius is reducible, either by increased pressure of draw or by thinning the wall of the tubing. In view of the mould difficulties encountered in the work at 4000 lbs/in^2, higher pressures are not recommended as a solution. The stiffness of the drawn tubing indicates a reduction to .012" or .015" wall thickness would not result in an impractical softness of finished drawn coil, and in addition would lighten the coil

2. In order to avoid the double handling of the tube, with annealing between the steps, a larger cross sectional diameter of tubing would help. If a large enough diameter, such that the 35% increment on base water volume resulted in a completely formed coil, a one-step process of drawing would result. This step is tempting, but from experience to date with the handling of coils in the mould, it may be delicate in operation. The difficulties encountered in placing the coil in the mould thread increased tremendously as the coil approached the size of the thread recess, as from previous drawing. The sectional form of the tubing deforms and the dimension of the coil parallel to the axis of the mould increased as the coil is wound around the mould. If the coil once begins to bind against the sides of the thread in the mould, as it is wound around the mould, a very delicate situation arises. No amount of manipulation from the outside will urge the coil safely into the mould thread. The coil tends to collapse and form two "wrinkles" or "bends" at the outside of the groove As these "beads" are outside the 18" diameter of the mould sleeve, the mould cannot be assembled with such "beads" present. With a 3/4" round-tube section and a thread recess of 3/4" by 7/8", at times considerable difficulty was experienced in urging the coil deep enough to enable the outer sleeve to be put in position and not cut a portion of the overlapping coil. A further difficulty in trying to increase the starting tubing size above 3/4" O.D. comes in the essential 75' length. The New England firm's tube-drawing facilities do not enable them to extrude a tube of over 3/4" diameter in a length of 75'. Additional diameter of tubing could only be obtained by sacrificing coil length. For our test it was decided to use the 75' coil exclusively. Use of the mould indicates that lengths of 150' could be successfully formed, with redesign of mould.

Appendix C

Attenuation Tests

Two sections of coiled echo line prepared by Mr. Flavin were given attenuation tests as described below:

The power source used was the output of a 20 db directional coupler installed in a K-band radar of a frequency of 23,800 mc/sec. The power measuring equipment used was a TS-254/UP battery operated wattmeter

Tapered transformers 3½ inches long which transformed from the TE_{10} mode in ½" x 1/4" K-band waveguide to the TE_{01} mode in the echo line guide were attached at each end of the echo line sections. These tapered adapters were provided with the old style Radiation Laboratory round fittings, and adapters from these to UG-116/U and UG-117/U were placed on each transformer with round choke-flange joints. The standing wave ratios of the transformer were not measured, but the attenuation observed through the combination of adapters and transformers described above, without the echo line, was .4 db.

Power measurements were made first at the directional coupler output, then at the end of the echo line attached to the directional coupler output. The difference in level was considered the attenuation of the echo line plus adapters.

Results:

	Attenuation
Adapters alone	.4 db
Adapters plus section No. 1	3.7 db
Adapters plus section No. 2	very high attenuation

At this point air was blown through section No. 2 and 50 to 100 cc of liquid water came out, evidently water remaining from the fabrication process. Dry air was blown through the line for about five minutes to assure that the internal surface was dry. Section No. 1 was also blown out with air, discovering a small quantity of black dust presumably cupric oxide.

	Attenuation upon remeasurement	
Adapters plus section No. 1	2.1 db	(.0293 db/ft)
Adapters plus section No. 2	2.7 db	(.0298 db/ft)

Section No. 1 was 58 feet long. The external dimensions were .948" x .770", by measurement with a rule, and the corners were rounded on an external radius of 3/16".

Section No. 2 was 77 feet long. The external dimensions are as for Section No. 1, save that the corners are rounded on a larger radius, 1/4" external measure. Both tubes are derived from 3/4" round tubing of .027" wall thickness, which yields a computed wall thickness of about .019" for the echo line. Both lines were bent into a helix, with the E vector parallel to the axis of the helix. The outside diameter of the helix was 18-1/4". Lengths are measured on the outside diameter of the coiled tubing.

It was noted that the attenuation of the longer section was a function of torsional stress applied to the helix. This might have been due to either a poor connection or to mode trouble. No such effect was observed with the shorter section.

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TSDIC FORM 60 (13 MAR 47)

AUTHOR(S)		ATI- 13823
Wolf, J. M.	DIVISION: Electronics (3) SECTION: Antennas (9) CROSS REFERENCES: Wave-guides (97985) Attenuation - Measurement (12825)	ORIG. AGENCY NUMBER: R-974 REVISION

AMER. TITLE: K-band echo line

FORG'N. TITLE:

ORIGINATING AGENCY: Massachusetts Inst. of Technology, Radiation Lab., Cambridge

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		Unclass.	Mar '46	14	4	diagrs, graphs

ABSTRACT

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